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RESEARCH PAPER

Exogenous application of 4-chlorophenoxyacetic acid on morphological and yield traits of tomato (*Solanum lycopersicum* L.) during summer cultivation

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Abstract

Tomato (*Solanum lycopersicum* L.) is one of the most economically important vegetable crops in Pakistan. However, its productivity is severely limited during the summer season due to high temperature and humidity, which adversely affects reproductive processes such as pollination, fruit setting, and flower retention. This study was conducted to evaluate the effect of exogenous application of 4-chlorophenoxyacetic acid (4-CPA), a synthetic auxin, on the growth and reproductive traits of two tomato cultivars, Roma and VCT-1, under summer climatic conditions in Islamabad. A field experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications, using foliar sprays of 4-CPA at concentrations of 0 (control), 15, 30, and 75 ppm. Using a Randomized Complete Block Design (RCBD), four doses of 4-CPA (0, 15, 30, and 75 ppm) were sprayed on leaves at the research farm, National Agricultural Research Centre (NARC), Islamabad. Results revealed that 4-CPA application significantly enhanced plant height (59 %), leaf number (52 %) and fruit set (3.75 times) with the 75 ppm concentration showing the most promising effects on Roma and VCT-1. However, high humidity and temperature fluctuations remained major constraints, impacting anther dehiscence, stigma receptivity, and pollination efficiency. These findings suggest that 4-CPA can mitigate the adverse effects of summer stress by promoting vegetative growth, accelerating reproductive development, and enhancing fruit set. The 75-ppm concentration was the most effective across both cultivars. However, optimization of application timing and concentration, along with integrated stress and pest management, is recommended for sustainable improvement in tomato productivity under heat-stressed conditions. © 2025 The Author(s)

Keywords: Agronomic parameters, Growth regulators, Heat stress, Reproductive stage, *Solanum lycopersicum* L.

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Introduction

The tomato (*Solanum lycopersicum* L.) belongs to the Solanaceae family and is one of the most widely cultivated and consumed vegetable crops globally (Kumar et al., 2020). Originating from tropical America, the tomato has become a staple in both commercial agriculture and home gardening due to its nutritional value, economic importance, and culinary versatility (Van Andel et al., 2022). It is a rich source of vitamins A, B, and C and exhibits antibacterial properties that are beneficial for health, including wound healing (Tam et al., 2021; Irina et al., 2024). These bioactive compounds have a wide range of physiological properties, including anti-inflammatory, anti-allergenic, antimicrobial, vasodilatory, antithrombotic, cardio-protective, and antioxidant effects (Braga et al., 2016). Tomatoes are also rich in carotenoids, representing the main source of lycopene in the human diet (Viuda-Martos et al., 2014). Tomatoes also have naturally occurred antioxidants vitamin C and E (Khan et al., 2021) as well as large amounts of metabolites, such as sucrose, hexoses, citrate, malate and ascorbic acid (Li et al., 2018). Despite its adaptability to various agro-climatic zones, tomato production is significantly affected by environmental stresses, particularly heat stress during summer cultivation. High temperature negatively influences multiple developmental stages, especially flowering and fruit set, which are more sensitive than vegetative parts such as stems and leaves (Rajametov et al., 2021; Menzel, 2023). Temperatures exceeding the optimal threshold typically above 29 – 30 °C (84 – 86 °F) for prolonged periods can result in flower abortion, poor pollination, fruit drop, reduced seed development, and overall decline in yield and fruit quality (Chauhan & Thakur, 2025; Patiyal et al., 2025). Additional effects of heat stress include uneven ripening, reduced shelf life, changes in taste, and the occurrence of physiological disorders such as sunscald and tomato pox (Ayenan et al., 2022; Sousa et al., 2022).

To address these challenges, the use of plant growth regulators (PGRs) has gained increasing attention as an agronomic strategy for improving stress tolerance,

enhancing reproductive success, and boosting overall productivity. PGRs are bioactive compounds that regulate physiological and developmental processes in plants, including cell division, elongation, and fruit development (Rajala & Peltonen-Sainio, 2024). Among them, auxins such as indole-3-acetic acid (IAA) and synthetic analogs like naphthaleneacetic acid (NAA) are known to improve fruit set and retention by modulating hormonal balances (Khan & Nabi, 2023). Similarly, gibberellins (e.g., GA_3) stimulate stem elongation, leaf expansion, and flowering, contributing to increased yield and biomass (Rahma et al., 2024). Research has demonstrated that exogenous application of auxins and gibberellins can significantly improve the growth and productivity of various crops under stress conditions. For instance, foliar sprays of GA_3 and NAA have shown beneficial effects on fruit quality and yield in okra, citrus, and other horticultural crops (Abdullah et al., 2024; Hussain et al., 2025). These findings demonstrate the potential role of PGRs in mitigating the adverse effects of high temperatures on sensitive stages of plant development.

4-Chlorophenoxy acetic acid (4-CPA) is an auxin that influences fruit setting in tomatoes (Ahmed et al., 2025). In particular, applying 4-CPA after anthesis increased the percentage of fruit set, number of fruits per plant, weight, fruit diameter, number of fruits per cluster, and yield per cluster at lower temperatures (Poonia et al., 2024). 4-CPA is a plant growth regulator that enhances fruit set during summer (Sasaki et al., 2005) and can also induce parthenocarpy and fruit development without fertilization (Mariotti et al., 2011). When the synthetic auxin 4-CPA was applied to flowers, it successfully induced parthenocarpic ovarian growth (Mariotti et al., 2011). It is widely used in tropical and subtropical tomato-growing regions to enhance fruit set during periods of high temperature, when natural pollination and fertilization processes are compromised (Singh et al., 2023; Rahman et al., 2024). The Asian Vegetable Research and Development Center (AVRDC) recommends 4-CPA as a practical and effective solution for ensuring fruit development during summer cultivation. Despite its proven efficacy in other regions, the performance of 4-CPA under specific agro-climatic conditions, such as those in Islamabad, remains under researched. Moreover, the differential response of various tomato cultivars to 4-CPA application, particularly under summer heat stress, is not well-documented. Understanding these interactions is crucial for developing context-specific agronomic recommendations. Therefore, the present study was undertaken to evaluate the impact of exogenous application of 4-chlorophenoxyacetic acid on the morphological and yield traits of tomato during summer cultivation. The research specifically aims to determine the effectiveness of 4-CPA in improving fruit set, plant growth, and yield performance under high-temperature conditions, and to identify cultivar-specific responses that could guide future tomato breeding and management strategies in heat-prone regions.

Materials and Methods

Study site and soil properties

The study was conducted at the Vegetable Crops Research Program, National Agricultural Research Centre (NARC), Islamabad, Pakistan (Latitude: 33.42°N; Longitude: 73.08°E; Elevation: 683 meters above sea level). The experimental site's soil had a loam texture with a pH of 7.4 and an electrical conductivity (EC) of 0.45 dS m^{-1}. Soil nutrient analysis revealed concentrations of 28.4 mg kg^{-1} nitrate-nitrogen (NO_3^-–N), 7.07 mg kg^{-1} available phosphorus (P), and 203 mg kg^{-1} exchangeable potassium (K). The soil bulk density was recorded as 1.40 g cm^{-3} at a depth of 0 - 15 cm and 1.45 g cm^{-3} at 15 - 30 cm depth.

Plant resources and nursery management

Two tomato varieties namely Roma and VCT-1 were obtained from Vegetable Research Program, National Agricultural Research Centre (NARC), Islamabad, Pakistan. Seeds were sown in August in multiport trays filled with a growing mixture of soil, sand, and well-decomposed farmyard manure (FYM) in a 1: 1: 1 ratio. The trays were maintained under a polythene tunnel to support optimal seed germination and seedling development.

Field preparation and transplanting

The experimental field was ploughed and leveled prior to transplanting. The field was fertilized with 20 tons per hectare (t ha^{-1}) of FYM, and a basal dose of chemical fertilizers was applied at the rate of 55 kg ha^{-1} nitrogen (N), 80 kg ha^{-1} phosphorus (P_2O_5), and 32 kg ha^{-1} potassium (K_2O) using urea, di-ammonium phosphate (DAP), and potassium sulfate as sources. Forty-five-day-old seedlings were transplanted into the main field using a Randomized Complete Block Design (RCBD). Plants were spaced 75 cm between rows and 50 cm within plants.

Treatment application

Four concentrations of 4-chlorophenoxyacetic acid (4-CPA), were prepared and applied as foliar sprays. The treatments were as follows: T1: Control (no 4-CPA application), T2: 15 mg l^{-1} 4-CPA, T3: 30 mg l^{-1} 4-CPA, T4: 75 mg l^{-1} 4-CPA. Each treatment was applied to both cultivars using a hand sprayer at the early flowering stage, and then repeated at the fruit-setting stage. The experiment was laid out in RCBD with three replications, and each replication consisted of five plants per cultivar.

Data collection

During the experimental period, various morphological and reproductive parameters were recorded from each plant to evaluate the effect of 4-CPA on tomato growth and yield. Plant height (cm) was measured from the soil surface to the apex of the main stem using a measuring tape. Plant spread (cm) was determined by measuring the horizontal width of the plant canopy in two perpendicular directions and taking the average. The number of days to flowering was recorded as the number of days from transplanting to the appearance of the first flower on each plant. Number of leaves per plant was counted manually

from the base to the top of the main stem. Field establishment percentage was calculated by recording the number of successfully established plants per treatment relative to the total number of transplanted seedlings. Percentage of successful flowering plants was determined by noting the proportion of plants that produced at least one flower. The number of flowers per plant was countedmanually at peak flowering. Fruit setting percentage was calculated by dividing the number of successfully developed fruits by the total number of flowers per plant and multiplying by 100. All measurements were taken carefully and consistently across all replications to ensure accuracy and reliability of the data.

Statistical analysis

The experiment was repeated three times under similar environmental conditions using the same materials. Data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics 21. To determine significant differences among treatment means, Duncan's Multiple Range Test (DMRT) was employed at a 5 % significance level ($p < 0.05$). Graphical representations of the data were created using GraphPad Prism software (version 5.03). All statistical procedures followed the methods outlined by Steel and Torrie (Abdullah et al., 2025)**.**

Results

Effect of 4-CPA on plant height

The application of 4-chlorophenoxyacetic acid (4-CPA) significantly increased plant height in both tomato cultivars compared to the control. The highest increase in plant height was observed at 75 ppm 4-CPA treatment, where VCT-1 and Roma plants exhibited a 50 % to 69 % increase in plant height, respectively. Additionally, lower concentrations of 4-CPA (15 and 30 ppm) also significantly enhanced plant height. In Roma plants, 15 and 30 ppm treatments resulted in increases of 18 and 32 %, respectively, while in VCT-1 plants, the increases were 24 and 48 %, respectively, when compared to their corresponding controls (Fig. 1).

Effect of 4-CPA on plant spread

Plant spread showed a significant increase in both tomato varieties following the application of 4-CPA, as compared to the controls. The maximum increase occurred in plant spread at the 75 ppm 4-CPA treatment, with VCT-1 and Roma showing 1.12 times and 92 % increases, respectively. Moreover, lower concentrations (15 and 30 ppm) also significantly enhanced plant spread. In Roma, plant spread increased by 24 % at 15 ppm and 53% at 30 ppm, while in VCT-1, the increases were 25 to 71 %, respectively, compared to the control (Fig. 2).

Effect of 4-CPA on number of days to flowering

The application of 4-CPA resulted in a reduction in days to flowering in both tomato varieties compared to the control. In the Roma variety, days to flowering decreased by 4.4 %, 5.9 %, and 9.2 % at 15 ppm, 30 ppm, and 75 ppm, respectively. Similarly, VCT-1 exhibited reductions of 4.7 %, 10.3 %, and 18.7 % at the corresponding concentrations. The greatest decrease in flowering time was observed at 75 ppm 4-CPA in both varieties (9.2 % in Roma 18.7 % in VCT-1). (Fig. 3).

Effect of 4-CPA on number of leaves per plant

A significant increase in the number of leaves per plant was observed in both tomato varieties with increasing concentrations of 4-CPA. In Roma variety, leaf number increased by 52 %, 1.21, and 1.69 times at 15 ppm, 30 ppm, and 75 ppm, respectively. Similarly, VCT-1 showed increases of 38, 65, and 111 % at 15 ppm, 30 ppm, and 75 ppm, respectively. These results indicate that 4-CPA positively influenced leaf development at higher concentrations 75 ppm (Fig. 4).

Effect of 4-CPA on field establishment

The application of 4-chlorophenoxyacetic acid (4-CPA) resulted in a slight but consistent reduction in field establishment in both tomato cultivars compared to the control. The maximum decrease in field establishment was observed at the 75 ppm treatment, with Roma and VCT-1 showing reductions of -12 % and -13 %, respectively. Moreover, other treatments of 4-CPA (15 and 30 ppm) also negatively affected field establishment. In Roma, field establishment declined by -3 % at 15 ppm and -7 % at 30 ppm, while in VCT-1, the respective reductions were -4 % and -7 % compared to their controls (Fig. 5).

Effect of 4-CPA on plant flowering

The application of 4-chlorophenoxyacetic acid (4-CPA) significantly enhanced flowering in both tomato cultivars compared to the control. The significant increase in the number of flowers was recorded at the 75 ppm treatment, where VCT-1 and Roma exhibited 1.78- and 1.56-fold increases, respectively. Lower concentrations of 4-CPA (15 and 30 ppm) also promoted flowering. In Roma, flower numbers increased by 31 and 87 % at 15 ppm and 30 ppm, respectively, while in VCT-1, the increases were 50 % and 1.07-fold at the same concentrations, compared to their corresponding controls (Fig. 6).

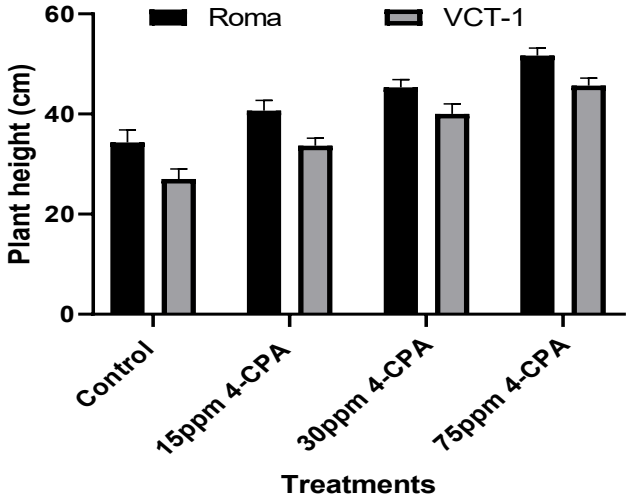

Fig. 1 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on plant height in tomato plants grown under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at $p \leq 0.05$.

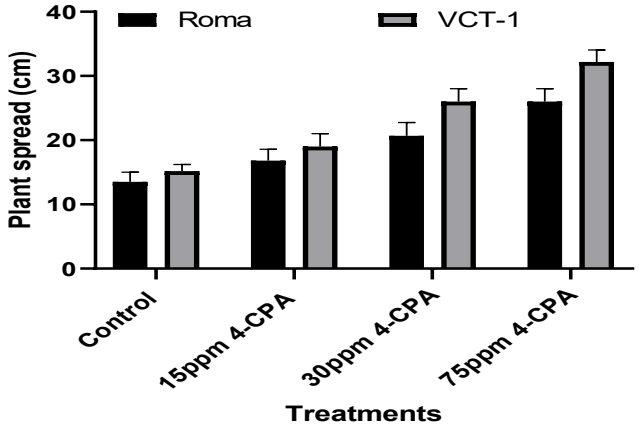

Fig. 2 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on plants spread in tomato plants grown under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at $p \leq 0.05$.

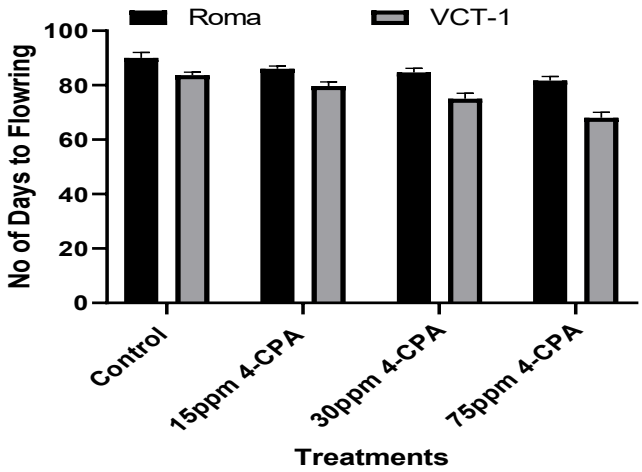

Fig. 3 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on number of days to flowering in tomato plants grown under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at $p \leq 0.05$.

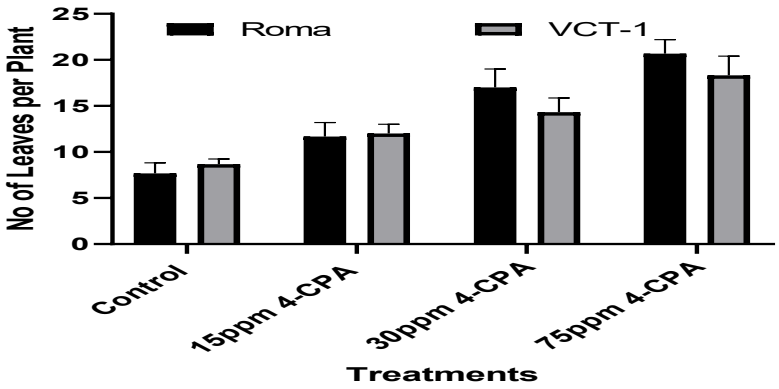

Fig. 4 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on No. of leaves per plant in tomato plants grown under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at p≤0.05.

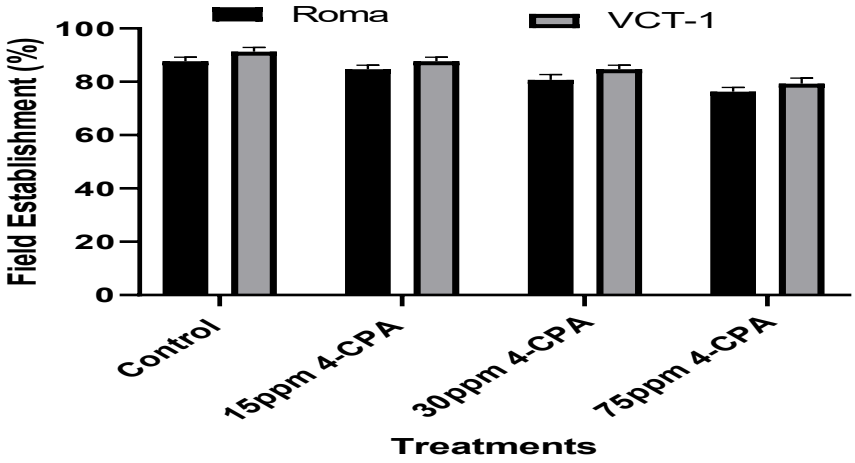

Fig. 5 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on Field establishment in tomato plants growth under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at p≤0.05.

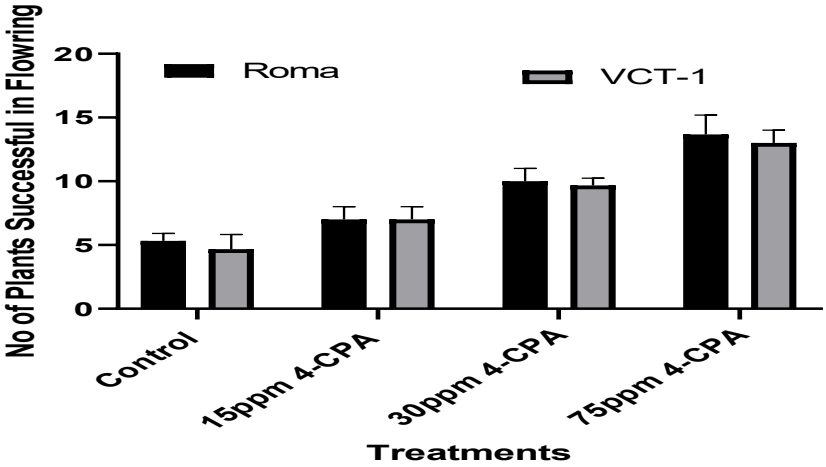

Fig. 6 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on plant flowering in tomato plants growth under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at p≤0.05.

Effect of 4-CPA on number of flowers per plant

A significant increase in the number of flowers per plant was observed in both tomato varieties with increasing concentrations of 4-CPA. In the Roma variety, flowers number increased by 41, 77 %, and 1.29 times at 15 ppm, 30 ppm, and 75 ppm, respectively. Similarly, VCT-1 showed increases of 68 %, 1.31 times, and 2.10 times at 15 ppm, 30 ppm, and 75 ppm, respectively. These results indicate that 4-CPA positively influenced flowers development at higher concentrations 75 ppm. (Fig. 7).

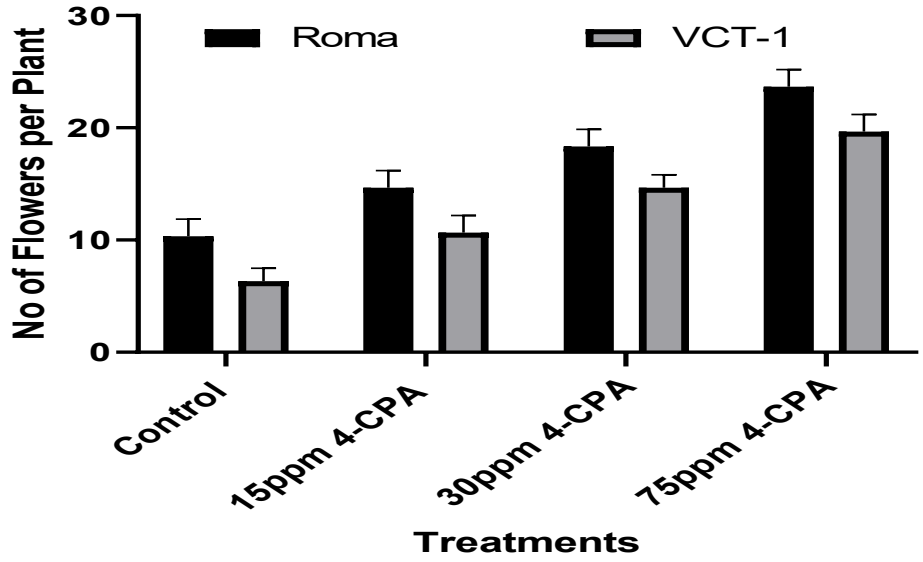

Fig. 7 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on number of flowers per plant, tomato plants growth under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at $p \leq 0.05$.

Effect of 4-CPA on fruit setting

The application of 4-chlorophenoxyacetic acid (4-CPA) significantly enhanced fruit setting in both tomato cultivars compared to the control. The highest increase in fruit setting was observed at 75 ppm 4-CPA treatment, where VCT-1 and Roma plants exhibited a 2.19 times and 3.75 times increase, respectively. Additionally, lower concentrations of 4-CPA (15 and 30 ppm) also significantly enhanced fruit setting. In Roma plants, 15 and 30 ppm treatments resulted in increases of 90% and 1.28 times, respectively, while in VCT-1 plants, the increases were 1.41 times and 2.33 times, respectively, when compared to their corresponding controls (Fig. 8).

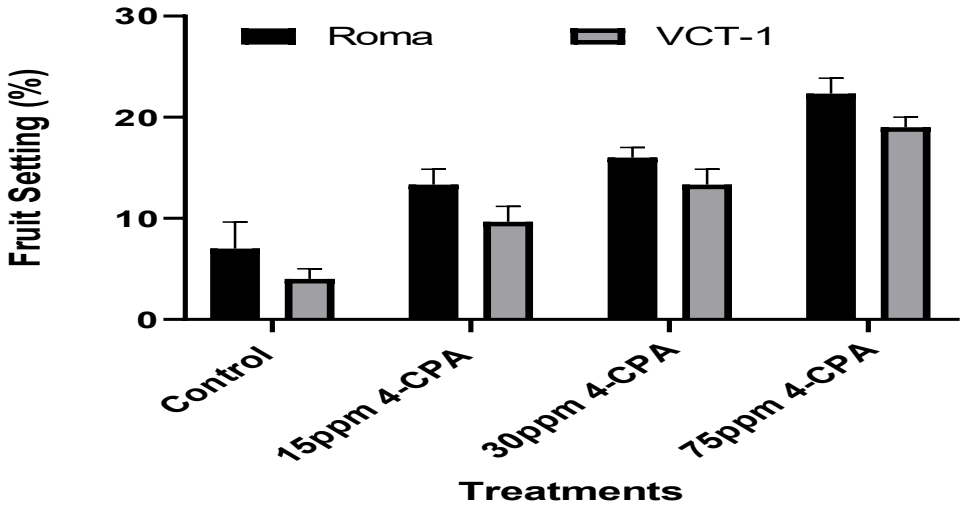

Fig. 8 Effect of exogenous 4-chlorophenoxyacetic acid (4-CPA) on fruit setting, tomato plants growth under summer conditions. Bars represent mean value of triplicates with error bars where different letters indicate significant difference among treatments at $p \leq 0.05$.

Discussion

Plant growth and development are influenced by two primary factors. The foremost among these are endogenous chemical messengers, known as hormones, which regulate the overall growth of the plant as well as the development of its specific organs. Information related to the environmental influence is conveyed by the second mechanism, which is made up of entry variables including light, water, temperature, and gravity. Thus, a complex interplay of genetic, hormonal, and environmental influences determines each plant's ultimate pattern of development and behavior. Because 4-chlorophenoxyacetic acid (4-CPA), a synthetic auxin analogous works identically to the natural auxin indole-3-acetic acid (IAA), it is crucial for fostering growth in plants. 4-CPA had a favorable impact on vegetative development in the current investigation by considerably increasing plant height in both tomato varieties. According to earlier research, auxin analogues stimulate cell elongation, division, and vascular differentiation, which increases shoot growth and plant height overall. These results are in line with those findings (Vanneste et al., 2025).

Growth regulators accelerate cell division and elongation by promoting photosynthetic activity, effective absorption, and nutrient uptake (Shah et al., 2023). Auxins promote plant development, improve flexibility, and soften the stem cell wall (Ren et al., 2025). Similar to this, 4-CPA considerably increased plant dispersion in both tomato cultivars, suggesting that it has a favorable effect on vegetative development. Following spraying, there were notable variations in plant spreading. It's possible that the 4-CPA treatment prevented a considerable amount of fluctuation after the spray. By influencing gibberellin activity, CCC's inhibitory impact probably decreased main axis development, encouraged the production of lateral shoots, and changed apical dominance. The application of 2 % 4-CPA greatly accelerated plant development, leading to more leaves, greater flowers and fruits per plant, and greater plant spreading (Rahman et al., 2024). Because of improved carbohydrate buildup and effective photosynthesis, this led to an increase in dry matter (Ba et al., 2020). On cultivars Roma and VCT-1, the control treatment showed the highest number of days to flowering, whereas 4-CPA 75 ppm showed the shortest number of days to flowering.

The use of plant growth regulators (PGRs) significantly changed the tomato cultivars LST-6 and PVB-4's production and quality attributes (Kumar et al., 2024). Both cultivars showed similar productivity and qualities when 30 µg/mL gibberellic acid (GA_3) and 75 µg/mL 4-chlorophenoxyacetic acid (4-CPA) were applied (Shukla & Shaikh, 2023). In comparison to the controls, 75 ppm 4-CPA on Roma and VCT-1 produced the most leaves per plant. The Roma and VCT-1 control group had the fewest amount of leaves. As seen in the JP-27 cherry tomato, where it boosted plant height, leaf number, and fruit output, applying a solution of 4-CPA dramatically improved growth and yield (Ahmad et al., 2017). development regulators promote plant development by enhancing photosynthesis, nitrogen absorption, and cell elongation (Shah et al., 2023). Under less-than-ideal field circumstances, the use of growth regulators considerably improved the growth performance of both tomato types, despite the control soil having greater nutrient levels. This result is in line with earlier research showing that external application of plant growth regulators can improve plant growth and offset nutritional stress by supporting physiological processes and hormonal balance (EL Sabagh et al., 2022). The 75 ppm 4-CPA-treated plants in both cultivars Roma and VCT-1 had the highest flowering being successful, flower number per plant, and fruit setting during this study when compared to the controls. These findings imply that 4-CPA is a useful plant growth regulator for improving reproductive tomato performance. According to previous research, 4-CPA stimulates ovary growth and decreases flower abscission in tomatoes by imitating auxin action, which improves fruit set and floral development (Karyagin et al., 2020). 4-CPA's function in enhancing reproductive qualities was confirmed by the considerable increase in flower and fruit number that resulted from foliar treatment, especially when exposed to environmental stress (Ahmad et al., 2025). When LST-6 received treatment with 75 µg/mL 4-CPA, the highest mean number of fruits per plant was recorded (Bhatia et al., 2023). 4-CPA dramatically increases tomato output, with the best results occurring at 22,222 plants per hectare, according to a study conducted in Nigeria (Chishti et al., 2020).

Conclusion

The vegetative development of tomato cultivars "Roma" and "VCT-1" was positively impacted by the administration of 4-chlorophenoxyacetic acid (4-CPA). However, there are difficulties in producing tomatoes during the hot and muggy season. While stigmatic fluid dries up by late morning, resulting in inferior development of fruit, high humidity inhibits anther dehiscence. As a result, unpollinated blooms decline, greatly lowering output. Furthermore, tomatoes are particularly vulnerable to insect infestations and illnesses, which worsen at this time and impact both quantity and quality.

Declarations

i. Ethics approval and consent to participate

Ethical approval and informed consent were not required for this study as it did not involve human participants, human data, or animals.

ii. Consent for publication

Consent for publication is not applicable.

iii. Data availability

All data generated or analyzed during this study are included in this article.

iv. Competing interests

Authors have declared that no competing interests exist.

v. Authors' contributions

G.J. designed the study. T.N. carried out the field experiments, contributed to data collection and wrote the initial draft of manuscript. A.M. contributed to the experimental design. A.L. assisted with experimental work, data interpretation, and literature review. N.N.N. performed statistical analyses. S.A. critically revised the manuscript. All authors reviewed and approved the final version of the manuscript.

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vii. Acknowledgement

Not applicable.

viii. SDGs addressed

Zero Hunger, Responsible Consumption and Production, Climate Action

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References

Abdullah, Khan, J., Aziz, S., Ali, S., Noor, T., Shoukat, S., Zaib, S., Maab, H., & Zia, M. A. (2025). Endophytic fungi from *Oxalis stricta* enhance growth, secondary metabolite production, and photosynthetic efficiency in maize (*Zea mays* L.). *Journal of Pure and Applied Agriculture, 10*(1), 83–93.

Abdullah, M., Anik, S. M., Nishi, N. J., Jahan, I., Khatun, M. A., Akther, F., & Rahman, M. H. (2024). Application of combined GA3 and NAA treatments to improve yield and quality of Okra (*Abelmoschus esculentus* L.). *Discover Agriculture*, *2*(1), 45. https://doi.org/10.1007/s44279-024-00055-w

Ahmad, H., Hassan, M. R., Laila, B., Mahbuba, S., & Jamal Uddin, A. F. M. (2017). Plant growth promoters on growth and yield of summer cherry tomato line (JP-27). *J. Bios. Agric. Res*, *12*(2), 1041-1047.

Ahmad, I., Bozhuyuk, M. R., Maryam, R. A., Ahmad, R., & Anjum, M. A. (2025). Applications of plant growth regulators in vegetables. In *Sustainable and innovative vegetable production in times of climate change: Concepts of olericulture* (pp. 311–323). https://doi.org/10.1007/978-981-96-6283-8_16

Ahmed, R. A. H., Abdellatif, I. M. Y., Oka, N., Kobayashi, M., Fuhrmann-Aoyagi, M. B., Todaka, D., Seki, M., & Miura, K. (2025). Application of 4-CPA or ethanol enhances plant growth and fruit quality of phyA mutant under heat stress. *Scientific Reports, 15*, Article 32388. https://doi.org/10.1038/s41598-025-32388-0

Ayenan, M. A. T., Danquah, A., Hanson, P., Asante, I. K., & Danquah, E. Y. (2022). Tomato (Solanum lycopersicum L.) genotypes respond differently to long-term dry and humid heat stress. *Horticulturae, 8*(2), 118. https://doi.org/10.3390/horticulturae8020118

Ba, Q., Zhang, L., Chen, S., Li, G., & Wang, W. (2020). Effects of foliar application of magnesium sulfate on photosynthetic characteristics, dry matter accumulation and its translocation, and carbohydrate metabolism in grain during wheat grain filling. *Cereal Research Communications*, *48*, 157-163.

Bhatia, J., Ghai, N., & Jindal, S. K. (2023). Influence of 4-CPA and GA3 on physiological, biochemical and yield attributes of tomato under high-temperature conditions. *Journal of Applied Horticulture*, *25*(2), 139-143.

Braga, P. C., Scalzo, R. L., Dal Sasso, M., Lattuada, N., Greco, V., & Fibiani, M. (2016). Characterization and antioxidant activity of semi-purified extracts and pure delphinidin-glycosides from eggplant peel (*Solanum melongena* L.). *Journal of Functional Foods, 20*, 411-421. https://doi.org/10.1016/j.jff.2015.10.032

Chauhan, A., & Thakur, D. S. (2025). Flower Drop and Thinning. In *Advances in Growth Regulation of Fruit Crops* (pp. 163-176). CRC Press.

Chishti, S. A. S., Aleem, S., Sharif, I., Nadeem, K., Parveen, N., & Najeebullah, M. (2020). Influence of 4-CPA growth regulator for enhancing yield of tomato during low night temperature stress. *Pakistan Journal of Agricultural Research*, *33*(2), 217-223.

EL Sabagh, A., Islam, M. S., Hossain, A., Iqbal, M. A., Mubeen, M., Waleed, M., ... & Abdelhamid, M. T. (2022). Phytohormones as growth regulators during abiotic stress tolerance in plants. *Frontiers in Agronomy*, *4*, 765068.

Hussain, F., Nawaz, M. A., Akram, M. T., Hayat, A., Asim, M., Raza, M. K., Afzaal, S., Haque, E. U., Ashraf, T., Zulfiqar, B., & Tariq, H. (2025). Foliar micronutrients application: A promising approach to improve reproductive growth and quality in Citrus reticulata Blanco. *Journal of Advanced Nutrition Science and Technology, 5*, 18–25. https://doi.org/10.15228/ANST.2025.v05.i01-2.p03

Irina, Z., Irina, P., Dmitriy, E., Inessa, P., Alla, C., Alena, P., & Natalya, H. (2024). Assessment of vitamin-and mineral-content stability of tomato fruits as a potential raw material to produce functional food. *Functional Foods in Health and Disease*, *14*(1), 14-32.

Karyagin, V. V., Prudnikova, O. N., & Rakitin, V. Y. (2020). 4-chlorophenoxyacetic acid as a regulator of ontogenesis in parthenocarpic fruits of tomato. *Russian Journal of Plant Physiology*, *67*, 802-808.

Khan, M. N., & Nabi, G. (2023). Role of Auxin in vegetative growth, flowering, yield and fruit quality of Horticultural crops-A review. *Pure and Applied Biology*, *12*(2), 1234-1241.

Khan, U. M., Sevindik, M., Zarrabi, A., Nami, M., Ozdemir, B., Kaplan, D. N., ... & Sharifi-Rad, J. (2021). Lycopene: Food sources, biological activities, and human health benefits. *Oxidative Medicine and Cellular Longevity, 2021*, 2713511. https://doi.org/10.1155/2021/2713511

Kumar, A., Kumar, V., Gull, A., & Nayik, G. A. (2020). Tomato (*Solanum Lycopersicon*). In *Antioxidants in vegetables and nuts-Properties and health benefits* (pp. 191–207). Springer: Berlin, Germany.

Kumar, M., Singh, S. K., Singh, A. K., Singh, D. K., Yadav, A. K., & Singh, U. (2024). Effect of plant growth regulators on growth and yield of tomato. *Vegetable Science, 51*(1), 188–191. https://doi.org/10.61180/vegsci.2024.v51.i1.25

Li, Y., Wang, H., Zhang, Y., & Martin, C. (2018). Can the world's favorite fruit, tomato, provide an effective biosynthetic chassis for high-value metabolites? *Plant Cell Reports, 37*, 1443-1450. https://doi.org/10.1007/s00299-018-2283-8

Mariotti, L., Picciarelli, P., Lombardi, L. & Ceccarelli, N. (2011). Fruit-set and early fruit growth in tomato are associated with increases in indoleacetic acid, cytokinin, and bioactive gibberellin contents. *Journal of Plant Growth Regulation, 30*, 405–415. https://doi.org/10.1007/s00344-011-9204-1

Menzel, C. M. (2023). A review of fruit development in strawberry: High temperatures accelerate flower development and decrease the size of the flowers and fruit. *The Journal of Horticultural Science and Biotechnology*, *98*(4), 409-431.

Patiyal, V., Rana, N., Rana, V. S., & Sharma, S. (2025). Fruit Drop and Parthenocarpy. In *Advances in Growth Regulation of Fruit Crops* (pp. 177-191). CRC Press.

Poonia, S., Raiger, P. R., Ram, M. & Kuri, R. (2024). Optimal use of plant growth regulators for improved growth, yield, and economic returns of winter tomato (*Solanum lycopersicum*) in arid regions. *Annals of Arid Zone, 63*, 107–112.

Rahma, S. A., Budiarto, R., Mubarok, S., & Abdullakasim, S. (2024). Impacts of gibberellin application on citrus: An overview from seed germination to fruit quality enhancement. *Kultivasi*, *23*(3), 364-374.

Rahman, F., Naimuzzaman, M., Shahab, T. B., Ahmed, F., Das, R. C., Tushi, S. S., ... & Roy, S. K. (2024). Effects of seaweed extract and 4-chlorophenoxyacetic acid (4-cpa) on improving growth and yield of Okra (*Abelmoschus esculentus* L.). *Journal of Agricultural Sciences and Engineering*, *6*(3), 141-153.

Rajala, A., & Peltonen-Sainio, P. (2024). Manipulating yield potential in cereals using plant growth regulators. In *Plant Growth Regulators in Agriculture and Horticulture* (pp. 27-70). CRC Press.

Rajametov, S. N., Yang, E. Y., Jeong, H. B., Cho, M. C., Chae, S. Y., & Paudel, N. (2021). Heat treatment in two tomato cultivars: A study of the effect on physiological and growth recovery. *Horticulturae*, *7*(5), 119.

Ren, A., Yang, Y., Huang, Y., Wan, Y., & Liu, Y. (2025). Exogenous auxin enhances stem straightness in *Paeonia lactiflora* cultivar by modulating cellulose development and vascular tissue. *Journal of Plant Growth Regulation*, *44*(2), 660-673.

Sasaki, H., Yano, T., & Yamasaki, A. (2005). Reduction of high temperature inhibition in tomato fruit set by plant growth regulators. *Japan Agricultural Research Quarterly, 39*(2), 135–138.

Shah, S. H., Islam, S., Alamri, S., Parrey, Z. A., Mohammad, F., & Kalaji, H. M. (2023). Plant growth regulators mediated changes in the growth, photosynthesis, nutrient acquisition and productivity of mustard. *Agriculture*, *13*(3), 570.

Shukla, V., & Shaikh, N. (2023). Study of the effect of consortia of PGPR on the growth of *Trichosanthes cucumerina* in a hydroponic system. *Journal of Applied Horticulture*, *25*(2), 112-116.

Singh, R., Ali, Z., & Kumar, V. (2023). Exploring the impact of plant growth regulators on growth dynamics and yield of potatoes (*Solanum tuberosum*). *Indus Journal of Animal and Plant Sciences*, *1*(2), 66-70.

Sousa, B., Rodrigues, F., Soares, C., Martins, M., Azenha, M., Lino-Neto, T., ... & Fidalgo, F. (2022). Impact of combined heat and salt stresses on tomato plants—insights into nutrient uptake and redox homeostasis. *Antioxidants*, *11*(3), 478.

Tam, C. C., Nguyen, K., Nguyen, D., Hamada, S., Kwon, O., Kuang, I., ... & Friedman, M. (2021). Antimicrobial properties of tomato leaves, stems, and fruit and their relationship to chemical composition. *BMC Complementary Medicine and Therapies*, *21*, 1-9.

Van Andel, T., Vos, R. A., Michels, E., & Stefanaki, A. (2022). Sixteenth-century tomatoes in Europe: Who saw them, what they looked like, and where they came from. *PeerJ*, *10*, e12790.

Vanneste, S., Pei, Y., & Friml, J. (2025). Mechanisms of auxin action in plant growth and development. *Nature Reviews Molecular Cell Biology*, *26*(9), 648-666. doi: 10.1038/s41580-025-00851-2

Viuda-Martos, M., Sanchez-Zapata, E., Sayas-Barberá, E., Sendra, E., Pérez-Álvarez, J. A., & Fernández-López, J. (2014). Tomato and tomato byproducts. Human health benefits of lycopene and its application to meat products: A review. *Critical Reviews in Food Science and Nutrition, 54*(8), 1032-1049. https://doi.org/10.1080/10408398.2011.623799

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